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SAFETY FEATURES AND CORE PERFORMANCE OF KALIMER

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Abstract

KALIMER (Korea Advanced LIquid MEtal Reactor) is an economically competitive, inherently safe, environmentally friendly, and proliferation-resistant liquid metal reactor which is now being developed by the Korea Atomic Energy Research Institute. A modular, pool-type sodium cooled KALIMER is currently in initial concept study phase with the goal of its construction to be completed by the year 2011.

KALIMER produces 333 MWe per reactor module with the employment of modular single component IHTS concept which can reduce the cost of IHTS by combining the three major components, i.e., steam generator, intermediate sodium pump, and intermediate sodium expansion tank into a single vessel thereby reducing the quantity, complexity, and space required by the IHTS.

Passive safety features of KALIMER design include the Reactor Vessel Auxiliary Cooling System (RVACS) which assures safety-grade decay heat removal and the Self-Actuated Shutdown System (SASS) for reactor trip. The core nuclear design will be largely governed by passive safety and reactivity control issues. KALIMER core is fueled with metallic fuel, and the initial core will be loaded with 20% enriched uranium metal fuel.

This paper summarizes the safety features of KALIMER design and the ATWS performance of Pu and U metal core options.

1. INTRODUCTION

The Korean national liquid metal reactor development plan was approved by the Korea Atomic Energy Commission in 1992, with the goal of developing a liquid metal reactor which can serve as a long term power supplier with competitive economics and enhanced safety. The KALIMER Program is now being led by the Korea Atomic Energy Research Institute (KAERI) with the objectives of developing an economically competitive, inherently safe, environmentally friendly, and proliferation-resistant fast reactor concept. A modular, pool-type sodium cooled KALIMER is currently in initial concept study phase with the goal of its construction to be completed by the year 2011.

The KALIMER plant will compete economically with contemporaneous alternative electrical generation options including both Advanced Light Water Reactors

(ALWRs) and fossil plants. This can be achieved by the simplification of the intermediate heat transfer system (IHTS), the elimination of rotating plug with the use of variable arm pantograph type fuel handling machine, and the introduction of seismic isolators.

KALIMER has enhanced safety features with the use of metallic fuel, Reactor Vessel Auxiliary Cooling System (RVACS), Self-Actuated Shutdown System (SASS), Gas Expansion Module (GEM) in the core, and the reduction of sodium piping above reactor vessel for the prevention of major sodium fires. Utilization of these enhanced safety features eliminates the need for diverse and redundant engineered safety systems so that "walk-away" safety characteristics are achieved. KALIMER accommodates unprotected anticipated transients without scram (ATWS) events without operator action, and without the support of active shutdown, shutdown heat removal, or any automatic system without damage to the plant and without jeopardizing public safety.

Environmentally friendly KALIMER has extremely low probability and amount of accidental radioactivity releases. The KALIMER core is loaded with metallic fuel which is recycled through pyroprocessing. Recycling of transuranic elements by this process would avoid the expense and potential long-term risk of their disposal in a geological repository, and would provide increased proliferation resistance.

The costs and schedules for KALIMER development will be minimized by standardizing the design and demonstrating the plant's operational and safety features in a full-scale test of a single nuclear steam supply system (NSSS). The modular design will allow a full commercial sized module and its associated NSSS equipment to be tested, eliminating the need to scale up the size of the components in a series of costly demonstration plants. The standard KALIMER design will be such that it can be certified by the Korea Institute of Nuclear Safety.

The KALIMER will be designed utilizing the available liquid metal reactor technology base, both foreign and domestic. Wherever cost advantages can be gained, latest state-of-the-art technology will be utilized.

2. KEY DESIGN FEATURES OF KALIMER

The standard KALIMER plant consists of power blocks which comprise multiple reactor modules with the power rating of 333 MWe per reactor module shown in Figure 1. Each power block consists of one or more reactor module systems and power conversion systems, together with their associated instrumentation, controls and auxiliary systems. The reactor core is designed to accommodate the flexible core envelope which permits use of various fissile materials and allows different breeding/ conversion ratio core configurations, including actinide burning capability. Table 1 summarizes the key design features of KALIMER.

The design features unique to KALIMER include the use of integrated steam generators, elimination of rotating plugs and simplification of in-vessel transfer machine, and volume reduction of intermediate sodium above the reactor vessel.

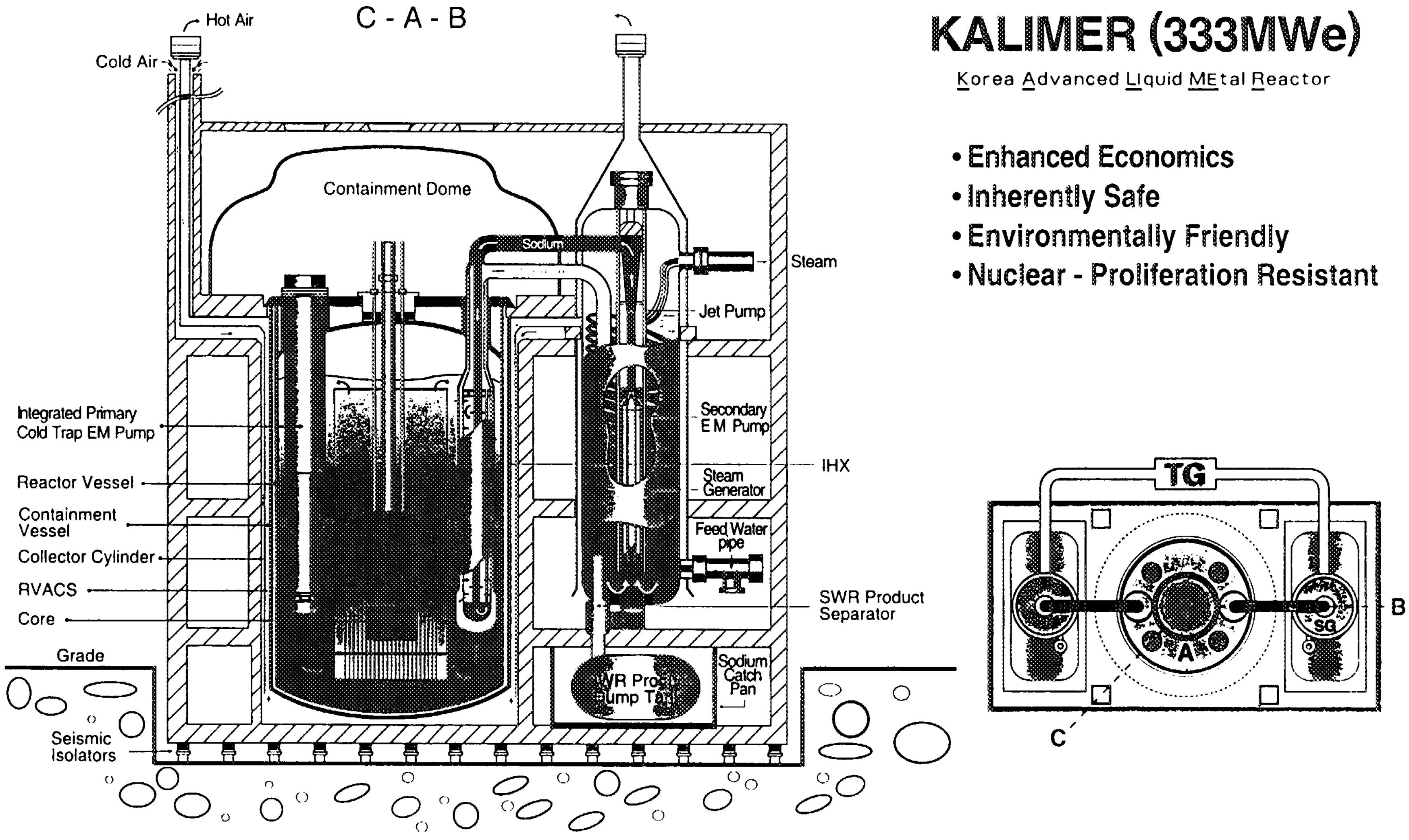

Figure 1. KALIMER Reactor Module and Steam Generator

Table 1. Key Design Features of KALIMER

Reactor	Modular Pool Type
Electrical Power	333 MWe / Reactor Module
Efficiency	40 % (target)
Fuel	Metal
Initial Core	20 w/o enriched U metal
Primary Sodium I/O Temp.	375 ^{0}C /530 ^{0}C (target)
Reactor Vessel	
Diameter	~ 9 m
Height	~15 m
Primary Pumps	
Type	Electromagnetic
Number	4
Number of IHXs	2
Steam Generator	
Number of Units	2
Type	Integrated with Secondary EM pump
Shutdown Heat Removal	RVACS
Reactor Shutdown System	SASS
Fuel Handling	Variable Arm Pantograph Type IVTM
Seismic Design	Seismic Isolation Bearing

KALIMER adopts the modular or consolidated IHTS concept which combines the three major components, i.e., steam generator, intermediate sodium pump, and intermediate sodium expansion tank, into a single compact component. This concept makes use of boiling water reactor (BWR) jet pump technology to reduce the number of electromagnetic (EM) pumps necessary for the required intermediate sodium flow rate, and thus reduces the diameter of the modular IHTS, which results in a substantial reduction in the cost of IHTS.

Elimination of rotating plugs is achieved by the use of variable arm pantograph type fuel handling machine which is plugged in during the refueling period for the in-vessel fuel transfer. In this case the upper internal structure which consists of the control rod driving guide tubes and mechanism, and the instrumentation plug will be pulled out for easy access of the fuel handling machine to reactor core.

The reactor building of KALIMER is on a 0.3g safe shutdown earthquake (SSE) seismic isolation system. This seismically isolated building is a super structure in which the reactor vessel and steam generators are located. Application of innovative seismic isolation system is expected to result in the improvement of economics and safety of KALIMER.

3. KALIMER SAFETY DESIGN OBJECTIVES

The overall goal of the KALIMER effort is to develop an advanced inherently safe, reliable, and marketable liquid metal cooled reactor power plant which will be economically competitive with alternative nuclear power plants. The safety design of KALIMER emphasizes accident prevention by using passive and natural processes, which can be accomplished by the following safety design objectives:

- Utilization of inherent safety features to eliminate the need for diverse and redundant engineered safety systems so that "walk-away" safety characteristics are achieved.
- Accommodation of unprotected ATWS events such as UTOP, ULOF, and ULOHS without operator action, and without the support of active shutdown, shutdown heat removal, or any automatic system without damage to the plant and without jeopardizing public safety.
- Low probability and amount of accidental radiation releases beyond the limits of the site boundary, which eliminates the need for detailed offsite evacuation planning, exercises, and early warning.

4. KEY SAFETY FEATURES OF THE KALIMER DESIGN

In order to achieve the above safety design objectives, the following design features are desired:

A. PASSIVE DECAY HEAT REMOVAL

KALIMER design requirements specify that each reactor module incorporates its own independent passive heat removal system which will protect the public health and safety following the complete loss of the normal heat removal system, without bulk AC power, without any operator action, following defined design basis events.

Reactor shutdown heat is normally removed by the turbine condenser using the turbine bypass. An Auxiliary Cooling System (ACS) is provided for cases when, due to maintenance or repair needs, an alternative shutdown heat removal method is required. The ACS induces natural circulation of atmospheric air past the shell side of the steam generator, and normal, natural circulation ACS operation is initiated by opening the exhaust damper. ACS operation in a natural circulation mode is expected to have the capability to maintain reactor temperatures below design limits.

In the highly unlikely event that the IHTS becomes unusable during power operation, for example, because of a main sodium pipe break or sodium dump, the reactor will scram and the RVACS will automatically come into full operation.

Temperatures of the reactor sodium and reactor vessel will rise, increasing the radiant heat transfer across the gap to the containment vessel and the heat transfer from the containment vessel to the upwardly flowing atmospheric air around the vessel. The temperatures and heat transfer by RVACS will continue to increase until equilibrium between reactor heat generation and RVACS cooling is established.

B. REACTIVITY CONTROL AND SHUTDOWN

In order to meet design requirements, two independent reactivity control systems employing different design principles will be provided. Each system ensures the reactor be maintained in a safe shutdown state under all operating and postulated accident conditions, assuming failure of the other system. The reactor protection system will have sufficient redundancy and independence to assure that no single failure results in loss of reactor function, and removal from service of any component or channel does not result in loss of the required minimum redundancy.

Negative feedback enhancers being considered include Gas Expansion Modules (GEMs) which enhance the negative reactivity feedback during a loss of flow without scram event, and a rod stop system which limits reactivity addition during a rod withdrawal without scram event.

KALIMER design adopts a passive shutdown system SASS which actuates by the naturally occurring physical phenomenon, i.e., saturation of magnetization of the ferromagnetic materials at Curie-point, without any external driving force. SASS consists of a Curie-point electromagnet and an articulated rod type neutron absorber assembly. Articulated rod can guarantee the insertion of the control absorber assembly into the reactor core even when the control rod guide tube is distorted due to the seismic load.

C. INHERENT NEGATIVE REACTIVITY CONTROL

The KALIMER is designed to provide a strong inherent negative reactivity feedback with rising temperature. This characteristic, combined with the RVACS heat removal capability, makes the KALIMER capable of safely withstanding severe undercooling and overpower transient events without scram.

As the temperature increases during an event, the negative feedback from Doppler, axial fuel expansion, radial core expansion, and control rod driveline expansion are activated, which generate a net negative reactivity for the core loaded with metal fuel. This feedback responds according to the associated time constants, to overcome the positive reactivity from the sodium density / void effect and any external source.

D. SEISMIC ISOLATION AND ELECTROMAGNETIC PUMPS

One of the challenges to standardized design and nuclear power plant siting has been the difficulty of incorporating a standard design on sites of differing seismic characteristics. The KALIMER reactor module design overcomes this problem by incorporating a seismic isolation to reduce the lateral seismic loads on the reactor structure and internals. The reactor module and steam generators with all safety related systems rest on seismic isolators, simplifying reactor component designs and significantly increasing safety margins. By placing the KALIMER NSSS on a seismically isolated platform, and by keeping the vessel diameter small, the seismic capability of KALIMER will allow it to be placed in most possible sites.

The primary and intermediate pumps are electromagnetic (EM). Synchronous motors, which provide coastdown power to the EM pumps, are on the same seismically isolated platform as the reactor module. The use of EM pumps and seismically isolated synchronous motors minimizes the potential for rapid coastdown in a seismic event, enhancing the natural safety characteristics of the plant.

One of the KALIMER safety design features also to be noted is the minimized volume of intermediate sodium above the reactor vessel for the prevention of major sodium fires should the sodium piping break occurs.

5. ACCOMMODATION OF ANTICIPATED TRANSIENTS WITHOUT SCRAM

KALIMER passively accommodates the ATWS events, and the plant response to the ATWS events meet criteria with adequate margins. KALIMER has inherent passive means of negative reactivity insertion and decay heat removal, sufficient to place the reactor system in a safe stable state for bounding ATWS events without significant damage to the core or reactor system structure.

In order to improve the KALIMER design and to investigate inherent safety features from the initial concept study phase, preliminary evaluation of ATWS performance for KALIMER core options has been performed.

A. CORE DESIGN OPTIONS

One of the options being considered for a KALIMER reactor core is the design which utilizes a homogeneous core configuration allowing a compact core and no fuel shuffling. The layout consists of 115 driver fuel assemblies, 42 radial blanket assemblies, 6 control rods, and 174 shield assemblies. The inner five rows of the core consist of low enrichment fuel assemblies and six control rods. The outer radial core section contains two rows of high enrichment fuel assemblies. Six control rods are located between two enrichment zones, and the driver fuel zones are surrounded by one row of radial blanket assemblies. There are no upper or lower axial blankets surrounding the core.

A comparison of the core performance parameters for the plutonium (Pu) and uranium (U) fueled KALIMER cores is summarized in Table 2. Since the U core is a direct substitution for the Pu core, i.e., both cores have the identical core layout, and assembly design data, the differences in the core performance parameters are directly attributed to the differences in the neutronics characteristics of the U-235 and fissile plutonium.

Table 2. Comparison of Core Performance Parameters

	Pu-U-Zr	U-Zr
Average Breeding / Conversion Ratio	1.12	0.71
Loaded Fissile Enrichment, w/o	11.1	19.8
Total Beta-effective	0.00355	0.00607
Reactivity Feedback Coefficients		
Doppler, Tdk/dt	-0.00309	-0.00313
Sodium Density, delta K	-0.02579	-0.00297
Axial Fuel Expansion, Hdk/dH	-0.18237	-0.18643
Radial Expansion, Rdk/dR	-0.45955	-0.46352
Sodium Void Reactivity, $	5.21846	-0.38580

The uranium fueled core requires a much higher fissile enrichment of 19.8 % in the feed fuel than that of 11.1 % for the corresponding plutonium core. Since U-235 is neutronically less effective than Pu-239 in a fast reactor system, a higher fissile enrichment is required to achieve criticality in the uranium fueled system.

The increase in the fissile enrichment has several important effects on the performance characteristics of the uranium core. The average conversion ratio is significantly lower due to the increased fissile depletion and reduced U-238 captures.

The total delayed neutron fraction for the uranium core is about 1.7 times larger than that of the corresponding plutonium core. This is due to an inherently higher beta-effective for the U-235 fission reaction. The higher delayed neutron fraction is expected to have a significant impact on the reactor kinetics during plant transients.

The uranium core has negative sodium density/void reactivity feedback coefficients, instead of the large positive void reactivity for the plutonium core. This is because i) the variation of capture-to-fission ratio due to spectral hardening is less pronounced in U-235, ii) the contribution of the higher plutonium isotopes, especially Pu-240, to the spectral shift reactivity is significantly smaller in the uranium core, iii) the impact of the spectral shift on the fast fission of U-238 is less important in the uranium core, and iv) the increase in the neutron leakage due to sodium voiding is more pronounced in the U-235 fueled core. The negative sodium void reactivity in the uranium core should have significant impacts on the plant operation and safety related issues.

B. ATWS SAFETY CRITERIA

According to the design requirement, KALIMER is to accommodate ATWS events, specifically UTOP, ULOF, and ULOHS, so that core damage leading to a safety challenge does not occur.

Conservative safety criteria are to be established in order to insure that the requirements for ATWS events are met. Safety criteria to be considered include the limited number of cladding failures, maintenance of primary boundary integrity, no sodium boiling, and no positive reactivity addition from fuel movement. Temperature limits are then to be set, based on current knowledge of experimental data, to insure that these safety criteria are met. The temperature limits are dependent on the specific fuel and cladding compositions, and are subject to revision as additional experimental test data become available.

Preliminary temperature limits for accommodated ATWS events of the KALIMER are 1820 ^{0}F (over which for less than two minutes) and 1880 ^{0}F for peak fuel temperatures of Pu and U metal fuels, respectively. In order to prevent sodium boiling, the temperature limit for sodium is set at 1750 ^{0}F when no sodium pumps are operating.

C. ATWS PERFORMANCE

A conceptual design of the plutonium and uranium core options for KALIMER has been evaluated. The uranium core was constrained to fit within the permanent reactor structure and to produce the same power as required for the plutonium fueled KALIMER core. ATWS events of UTOP, ULOF and ULOHS are selected for the safety margin assessment of the KALIMER design.

The objectives of ATWS performance analyses are to evaluate the inherent passive safety features and to compare the performance of the Pu and U cores. It should be noted that the KALIMER core option being analyzed has not been optimized yet, and thus there is a room for the improvement in its safety performance.

Due to its rapid progression of the UTOP event, for which case the safety margin is usually determined by the fuel centerline temperature, there is little effect of the reactor configuration on the consequences of this event.

The rapid coastdown of both primary and intermediate EM pumps in the case of ULOF event would cause rapid temperature rises which introduce the negative reactivity feedbacks to come in to play for the power decrease of the reactor. Analyses have been performed for the effects of primary pump coastdown on core safety.

For a ULOHS event, a loss of intermediate EM pump is assumed with the subsequent primary EM pump trip by the Thermal Shutoff System (TSS) which actuates based upon the core inlet sodium temperature and power levels.

All Primary Rods Withdrawal Without Scram (Figs. 2-7)

This event postulates that a malfunction in the reactivity controller causes the shim motor to continue to withdraw all of the primary control rods and that the Reactor Protection System (RPS) either fails to detect the event or the control rods fail to unlatch. The shim motors are assumed to withdraw the control rods at a rate corresponding to \$0.02 per second. The secondary control rods are completely withdrawn during normal operation, and it is assumed that these rods do not contribute to the reactivities inserted for this accident.

It is assumed that the primary and secondary sodium flows remain at rated conditions for this event and that the feedwater is sufficient to keep the sodium outlet temperature from the steam generator constant.

The results of \$0.20 UTOP transient for power and flow, the core temperatures, and the reactivity feedbacks are shown in Figures 2 through 7 for Pu and U cores.

For \$0.20 UTOP, the Pu core power level reaches its peak at 165% of rated condition and equilibrium at 125% power. The peak fuel and peak coolant temperatures are 1880 ^{0}F and 1423 ^{0}F, respectively. Core thermal expansion, which is the sum of axial fuel expansion, radial core expansion, and rod bowing, and control rod driveline expansion provide negative reactivities. Although the sodium expansion provides large positive reactivity, the net reactivity becomes negative due to core thermal expansion, Doppler, and control rod driveline expansion.

The core power level changes are similar for U and Pu cores, however, the peak fuel and peak coolant temperatures are much lower for U core due to the higher thermal conductivity of uranium metal fuel. The sodium expansion reactivity is much smaller for U core, but the Doppler and core thermal expansion reactivities are less negative due to the smaller temperature increases of the core.

Although the design meets the performance limits for ATWS events, the limiting condition appears to be the clad temperature at the elevated equilibrium conditions. This temperature must remain below the 1300 ^{0}F limit to prevent eutectic formation because the reactor could be in that state indefinitely.

For \$0.30 UTOP, the peak core power increases over 200% of rated power for both Pu and U cores. The peak fuel temperatures violates the limits of 1820 ^{0}F and 1880 ^{0}F, for Pu and U cores, respectively. However, the peak coolant temperatures are within the limits.

The performance of KALIMER Pu and U core options during selected ATWS events including UTOP is summarized in Table 3.

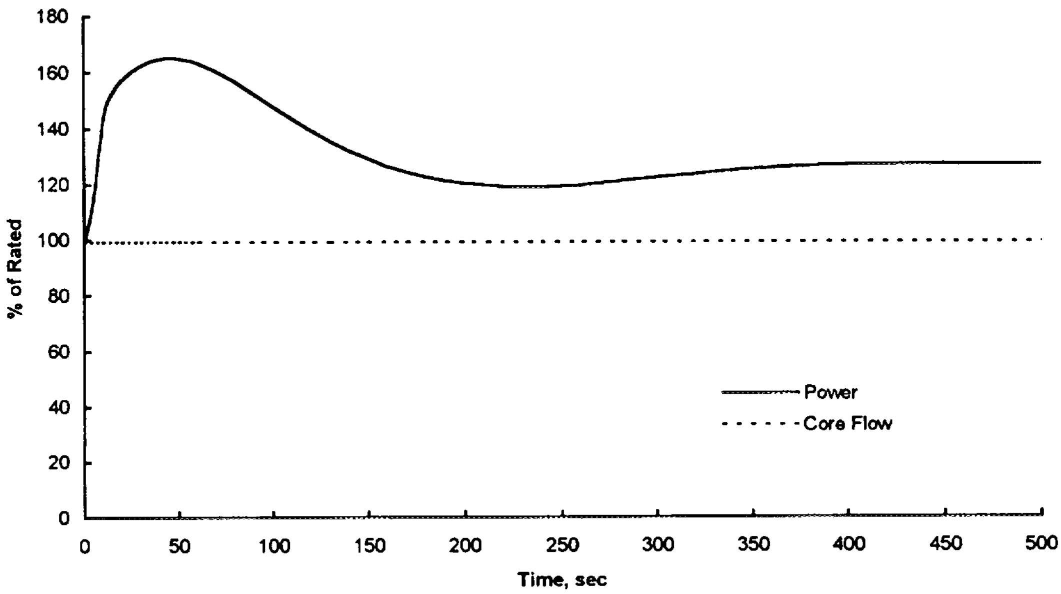

Figure 2. Power and Flow During $0.20 UTOP for Pu Core

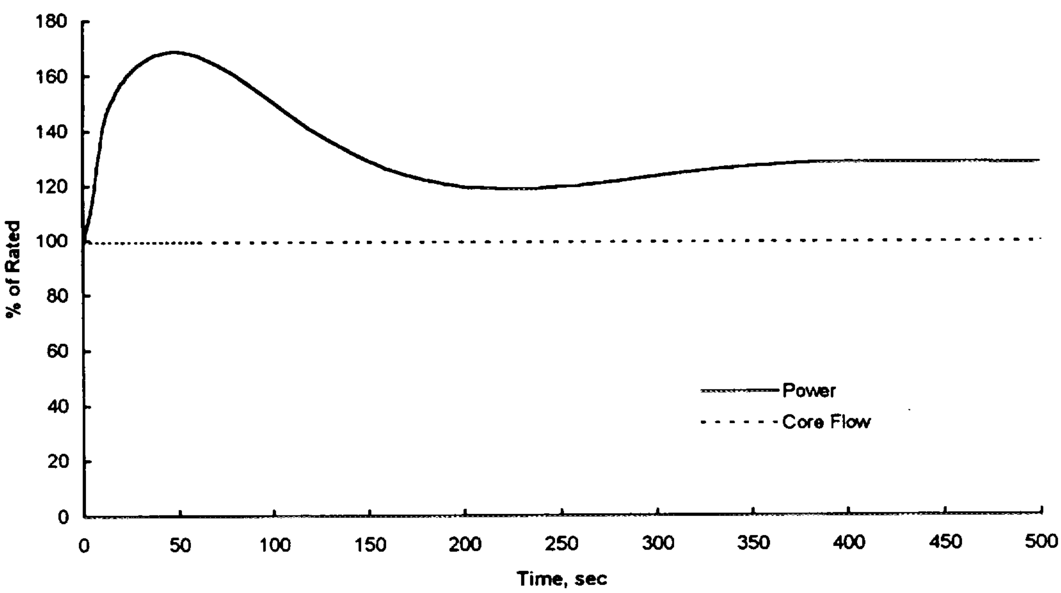

Figure 3. Power and Flow During $0.20 UTOP for U Core

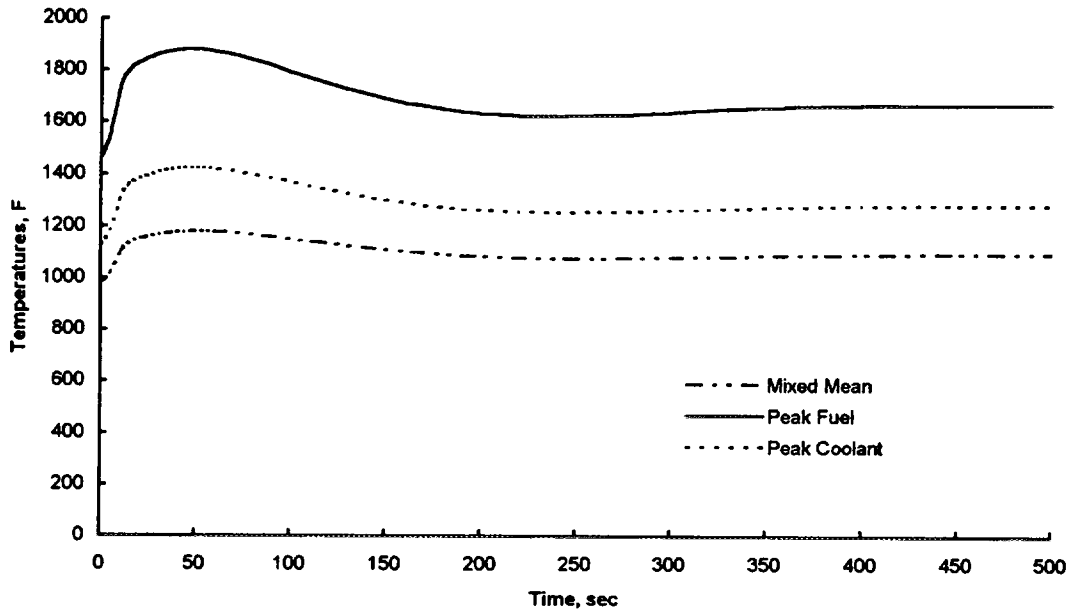

Figure 4. Temperatures During $0.20 UTOP for Pu Core

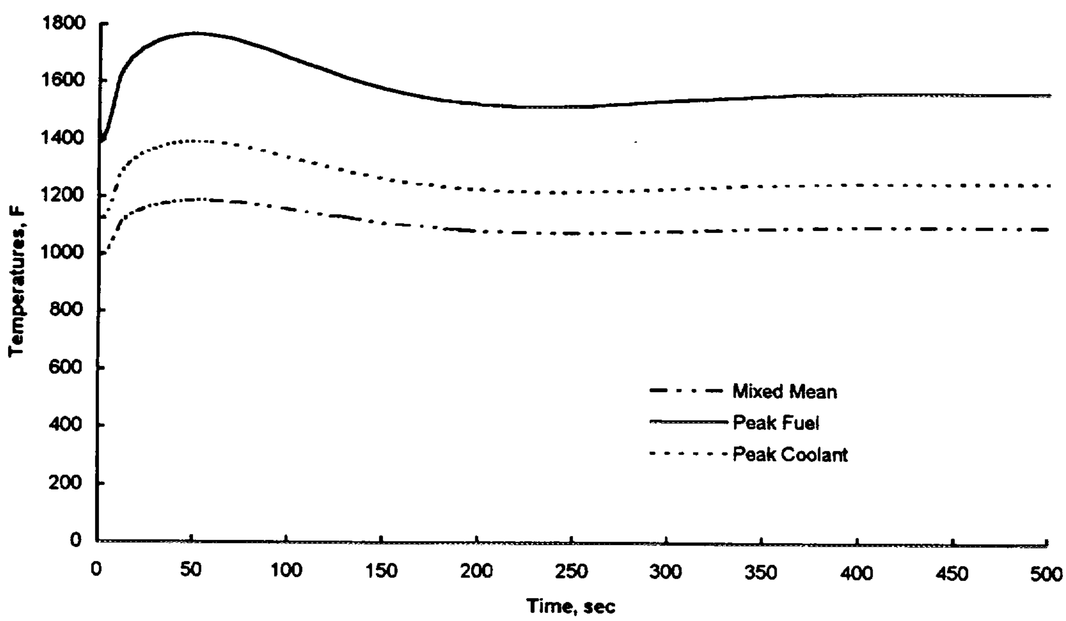

Figure 5. Temperatures During $0.20 UTOP for U Core

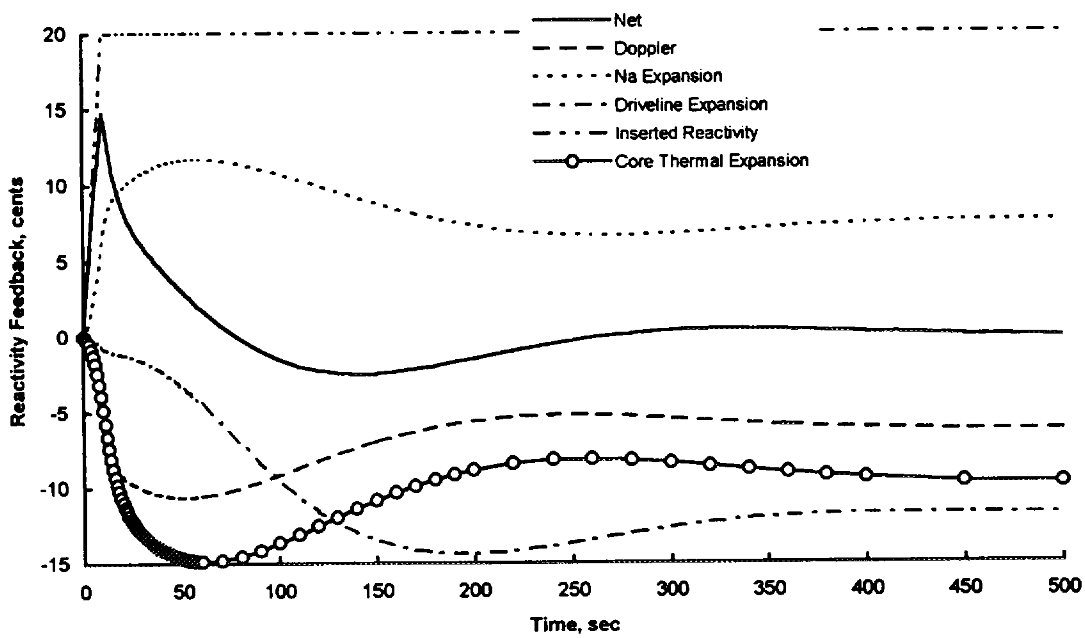

Figure 6. Feedbacks During $0.20 UTOP for Pu Core

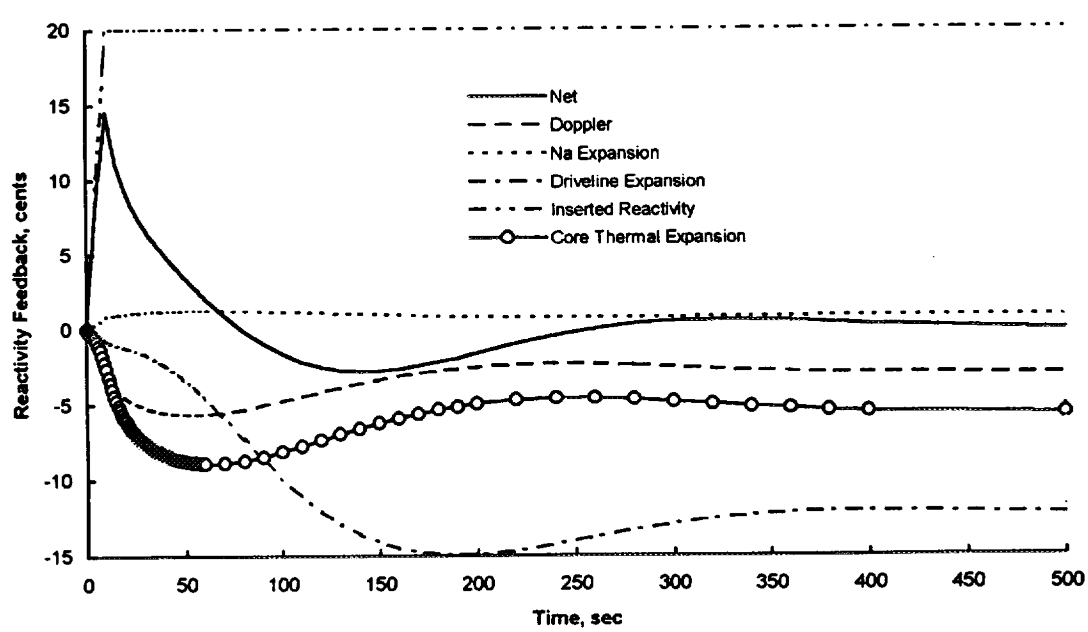

Figure 7. Feedbacks During $0.20 UTOP for U Core

Table 3. Summary of ATWS Performance of KALIMER Core Options

Events	Peak Power, %		Temperatures, ^0F Peak Fuel		Peak Coolant	
	Pu	U	Pu	U	Pu	U
Temperature Limits			1820	1880	1750	
100 % Power	100	100	1465	1445	1131	1131
\$0.20 UTOP	165	169	1880	1767	1423	1391
\$0.30 UTOP	206	209	2114	1974	1600	1553
Unprotected Loss of Primary Flow	100	100	1736	1609	1669	1544
Unprotected Loss of Intermediate Flow	100	102	1522	1445	1507	1390

Unprotected Loss of Primary Flow (Figs. 8-13)

For the ULOF event, the IHTS flow is assumed to be at the rated condition, and the primary pumps are assumed to coastdown. The heat removal from the reactor vessel by RVACS has not been modeled and the reactor heat is removed by the normal path of IHTS. After the coastdown, the primary pumps are in a low flow operation mode, providing about 13% of the rated primary flow. Although this would normally result in a scram due to a high flux-to-flow ratio soon after the initiation of the coastdown, it is assumed that either the RPS fails to detect the mismatch or the control rods fail to insert.

The transient results for power and flow, the core temperatures, and the reactivity feedbacks during the ULOF event are shown in Figures 8 through 13 for the Pu and U cores.

The primary flows drop to 49.64% of rated flow at 10 seconds after the initiation of the coastdown, and the flow rate is maintained at 13% of the rated flow for the low flow operation mode which begins at about 150 seconds. Core power decreases gradually due to the negative feedback effects, and U core power decreases more rapidly.

The peak temperatures occur after about 50 seconds, which is mainly because of gradual coastdown of the primary pumps. The temperatures reach maximum values of 1736 ^0F and 1669 ^0F for peak fuel and peak coolant temperatures, respectively, for Pu core. These temperatures are within limits. The peak fuel and peak coolant temperatures are much lower for U core due to the higher thermal conductivity of uranium metal fuel. There is a large safety margin for peak fuel temperature, and it is noted that the peak coolant temperature is a key parameter to meet the safety limits for this event.

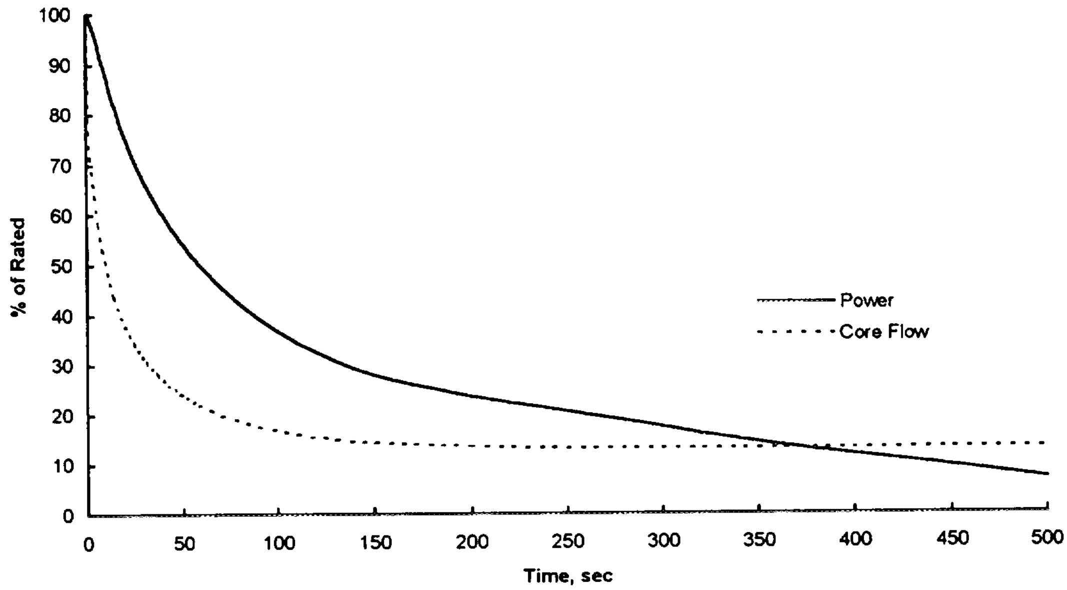

Figure 8. Power and Flow During ULOF for Pu Core

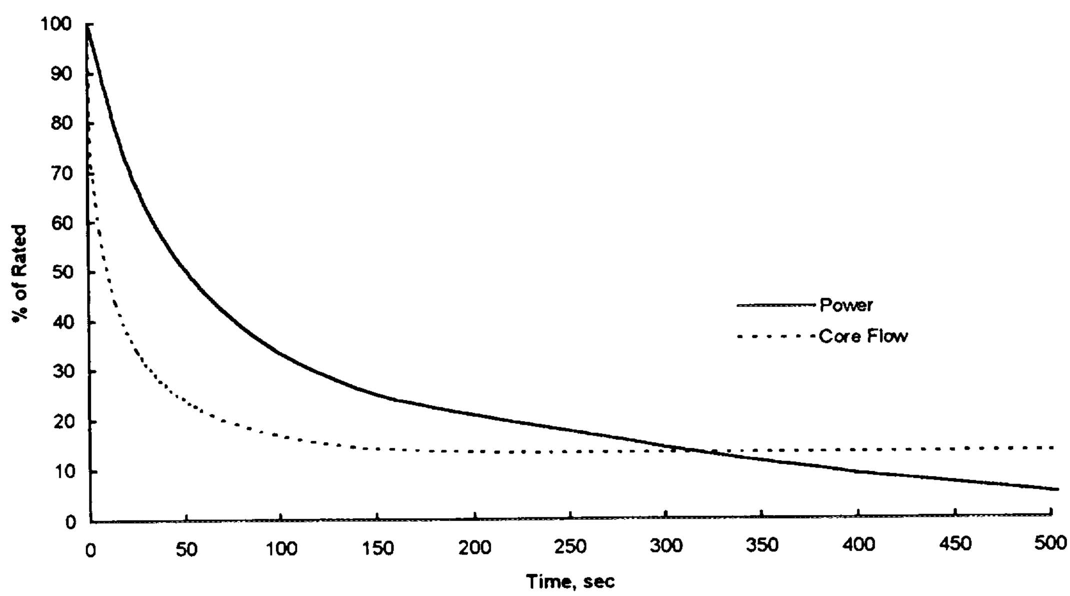

Figure 9. Power and Flow During ULOF for U Core

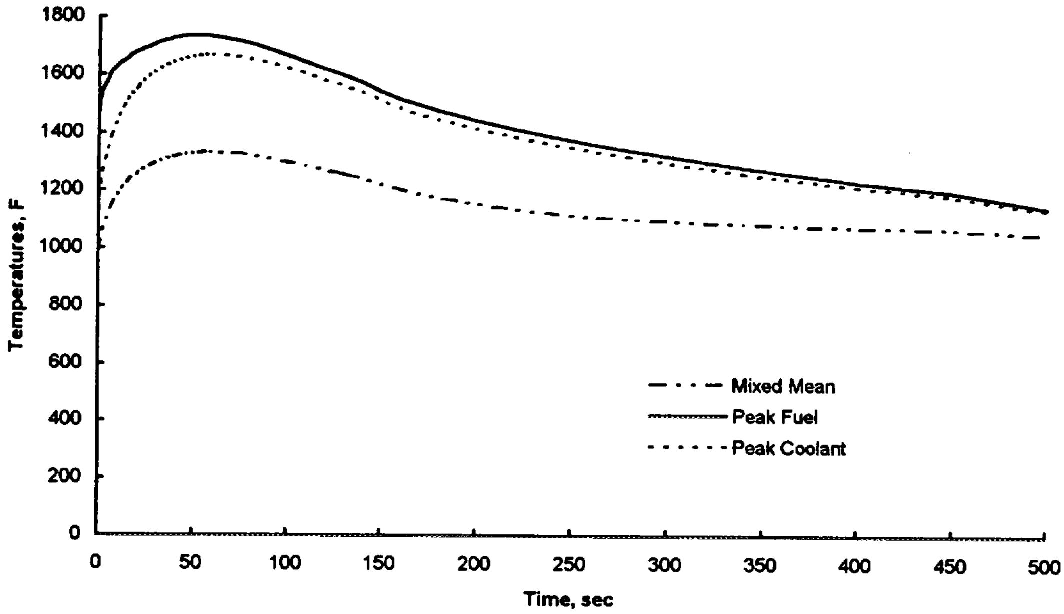

Figure 10. Temperatures During ULOF for Pu Core

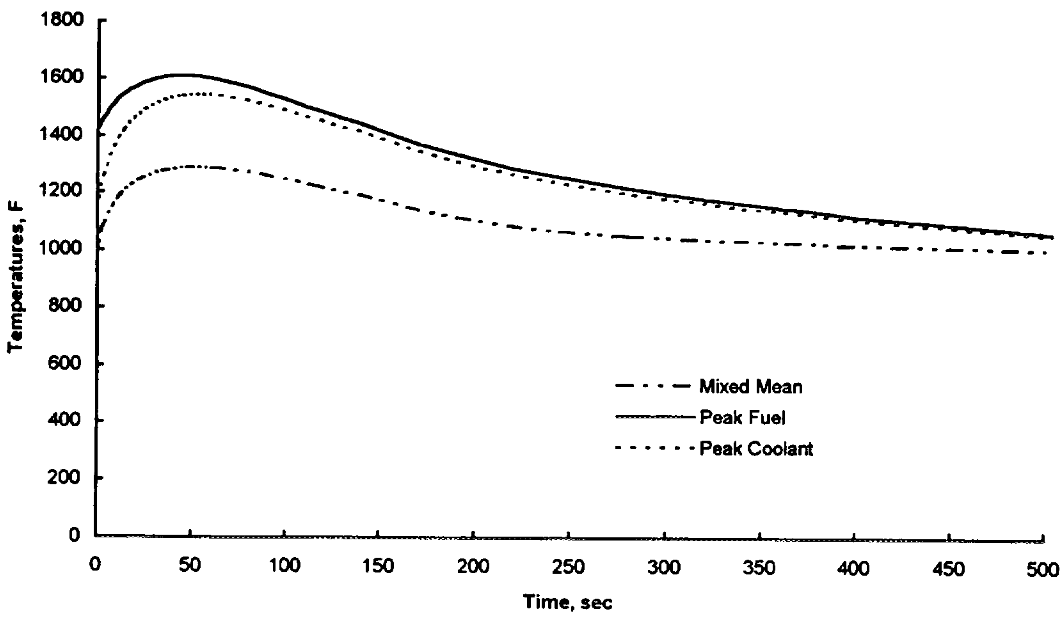

Figure 11. Temperatures During ULOF for U Core

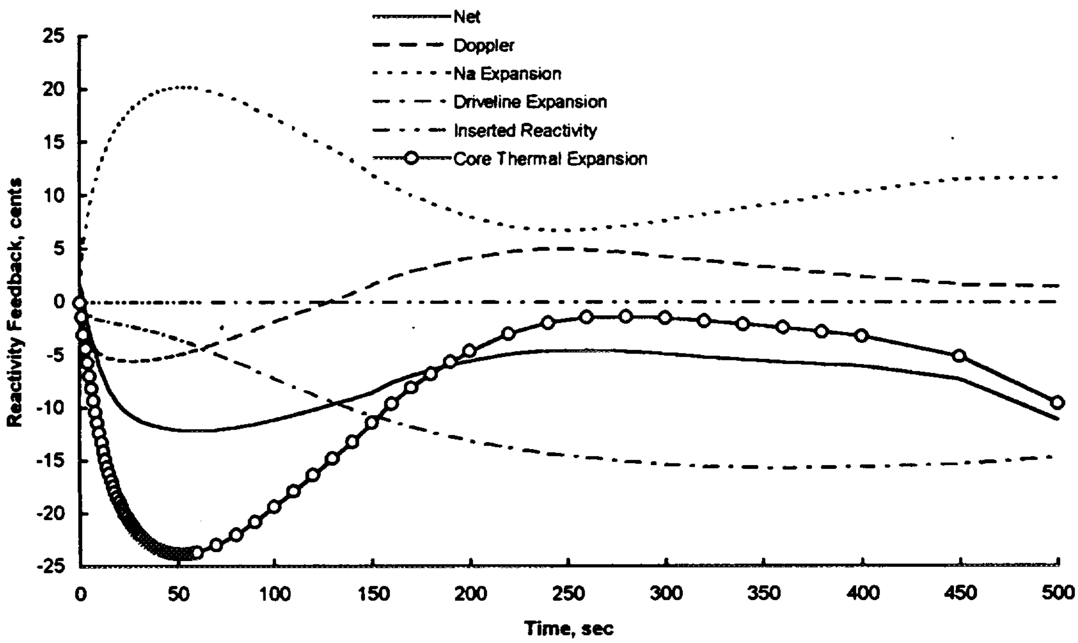

Figure 12. Feedbacks During ULOF for Pu Core

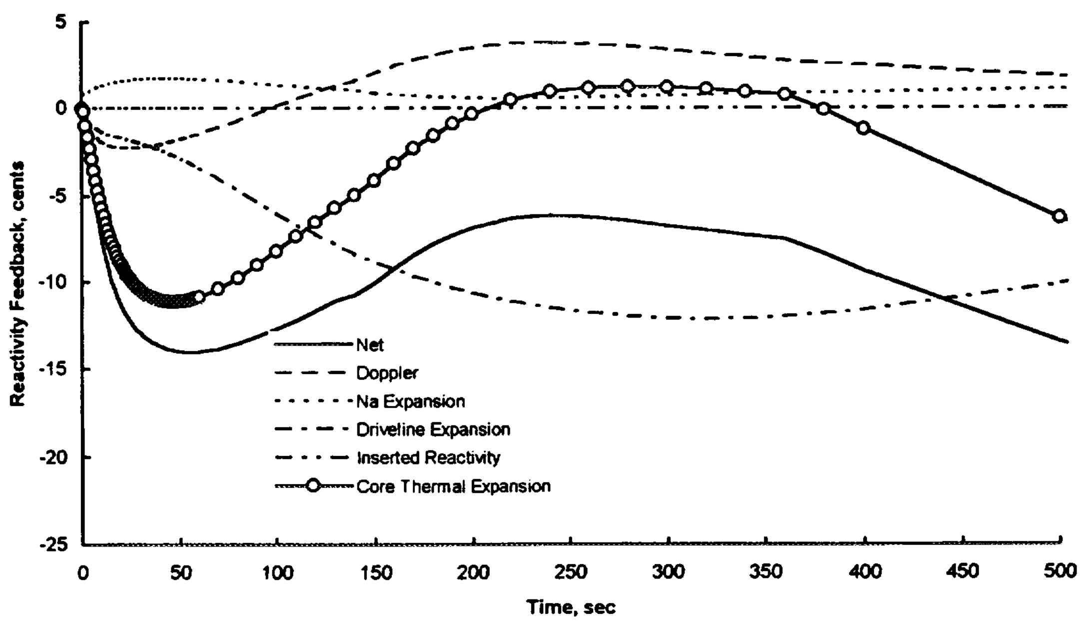

Figure 13. Feedbacks During ULOF for U Core

Although the sodium expansion reactivity is much larger for U core and core thermal expansion reactivity is more negative for the Pu core, net reactivity is always negative for both Pu and U cores.

The Pu and U cores which have been analyzed do not have GEMs. Adoption of GEMs in the core would increase the safety margin for the loss of primary flow events by the rapid introduction of a large negative GEM worth with the primary flow coastdown.

Unprotected Loss of Intermediate Flow

This event starts with a sudden loss of the normal heat sink by a stoppage of the intermediate sodium flow. The primary pumps are assumed to continue operating at rated conditions until tripped by the TSS. Although this event would normally be terminated by a scram due to high primary cold leg temperature, it is assumed that the RPS fails to detect the over-temperature. Current analysis of ULOHS event is performed without RVACS model, which limits the analysis to early stages of the event.

The core power decreases due to the negative reactivity feedback of the core caused by the increase in core temperatures for both Pu and U cores.

Peak coolant and fuel temperatures maintain steady-state temperatures initially, and then decrease slightly due to the reduced core power. The core temperatures increase rapidly to peak temperatures with the trip of primary pumps by the TSS.

Most dominant reactivity feedback effects are due to sodium expansion and core thermal expansion. Net reactivity is always negative due to the larger contribution from the core thermal expansion.

It should be noted that current analyses mainly focus on reactivity feedback effects at an early stage of the accident. The analysis of long-term performance is necessary with the model for RVACS heat removal.

6. CONCLUSIONS

The safety design of KALIMER emphasizes accident prevention by using passive and natural processes, which can be accomplished by the utilization of inherent safety features for the accommodation of unprotected ATWS events without operator action, and without the support of active shutdown, shutdown heat removal, or any automatic system. Low probability and amount of accidental radiation releases for KALIMER beyond the limits of the site boundary eliminates the need for detailed offsite evacuation plan.

Passive safety features of the KALIMER design include the RVACS and the ACS for the assurance of safety-grade and normal decay heat removal, respectively. KALIMER core is fueled with metallic fuel which has enhanced safety characteristics with negative feedback effects, and the detailed core design will be largely governed by passive safety and reactivity control issues. Features which are now considered include the SASS for passive reactor shutdown, rod stops which limit the reactivity addition during rod withdrawal event, and GEMs for the rapid introduction of negative reactivities during loss of flow event. Seismic isolation of the reactor and steam generator would also increase safety margins.

Improvement of the KALIMER design and assurance of the enhanced safety can be achieved by the preliminary evaluation of ATWS performance of KALIMER core options from the initial concept study phase. Results show that the temperature limits are met with margins for Pu and U cores whose performance would improve with a core design optimization and the introduction of passive features such as RVACS and GEMs.

ACKNOWLEDGEMENTS

The ATWS performance of KALIMER core options has been calculated using the computational tools of General Electric Nuclear Energy (GENE). Technical support and comments of Mr. A. J. Lipps and Dr. T. Wu of GENE are appreciated.

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